A whole life cycle approach under uncertainty for economically justifiable ballasted railway track maintenance

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A Whole Life Cycle Approach under Uncertainty for Economically Justifiable Ballasted Railway Track Maintenance

Abstract

Historically, railway track maintenance strategies have been based on engineering judgement taking into account available budgets and operational safety. This has led to insufficient concern of the socio-economic and environmental costs and benefits of track maintenance. Given the pressure to increase track utilization, the ageing infrastructure of railway networks, constrained maintenance budgets, the vertical separation of the ownership and operation of railway track infrastructure and rolling stock in many countries, and concerns about the environmental impacts of transport, there is a need to implement economically justifiable maintenance strategies. To this end, this paper presents for the first time an approach to appraise the investment in railway track maintenance. The approach uses a whole life cycle cost analysis under uncertainty approach which considers the costs and benefits of track maintenance to train operators, users and the environment. Monte Carlo simulation technique is used to address data uncertainties associated with the costs and benefits of track and train operation and maintenance. The proposed approach is applied to three different route types on the UK main-line railway network to compare a number of alternative maintenance strategies. In all the three cases more economically beneficial strategies were identified in comparison to those currently adopted.

JEL Codes: R420, R400, R490

1. Introduction

Railways are a major component of a sustainable transport policy in many countries since they are considered as green, efficient and a safe mode of transportation. Consequently, there is an increasing demand for the railway industry to expand capacity, availability and to transport goods and people at higher speeds. By 2025, railways are expected to carry 11,912 billion tonne-kilometre of freight and 5,149 billion passenger-kilometre worldwide, increases of 14.75% and 37.2% respectively from 2015 (SCI, 2017). However, in many countries, investment in the expansion of railway infrastructure has not kept up with the demand for increased usage. In the United Kingdom for example, passenger journeys have increased by approximately 4.8% between 2010-11 and 2016-17 without any significant increase in the amount of railway infrastructure, making the UK railways Europe's second highest congested railway network (ORR, 2017a). Similarly, during the same period passenger numbers in the United States have risen by 11% with only a 4.8% increase in railway track length (APTA, 2017) and in India the corresponding figures are 6.0% and 4.5% respectively (MoIR, 2016). Such increasing track usage will result in faster degradation and therefore higher maintenance costs. For example, the spending on maintaining railway track infrastructure in USA (FRA Class 1 rail roads), UK and India during 2016-17 was $9.8 million, $775 million and $2.08 billion respectively, which was 1.2%, 3.8% and 24% higher than in the previous year (AAR, 2016; ORR, 2017b; MoIR, 2017).

There is therefore an increasing pressure for railway infrastructure maintainers to make the best use of their available resources. For traditional ballasted railway track in particular, railway track maintenance directly affects the condition of the railway track and therefore, the likelihood of accidents, rolling stock fuel and maintenance costs, travel time costs and emissions. A well-maintained track not only guarantees ride comfort and safety but also increases the life of the track as well as track availability (due to the lack of imposition of speed limits). Therefore, to enable a green, efficient and safe railway system there is a need for effective asset management which systematically considers Whole Life Cycle Costs (WLCC) and benefits over the lifetime of the asset (See Figure 1) (ISO, 2017). Such an approach helps to identify cost drivers and cost-effective improvements, enables the comparison of alternative maintenance strategies and the prioritization of maintenance funds (Jun et al., 2007).

Currently however, maintenance decisions for ballasted railway infrastructure are largely based on time, tonnage or predetermined subjective maintenance standards, which ignore the costs of operation and maintenance. Thus, they fail to optimise maintenance interventions and therefore do not deliver maximum benefits (Atkins, 2011). This culture is gradually changing for the reasons described above and the sector is moving towards preventative condition-based maintenance (van Noortwijk et al., 2004). The publication of asset management standards and guidelines, which advocate WLCC, approaches, including ISO 15686-5 and EN 60300-3-3 has added additional impetus. As a result, railway infrastructure and rolling stock organisations have started to develop their own asset management tools which incorporate some WLCC principles. These initiatives have been supported by academic research, a summary of which is presented in Table 1.

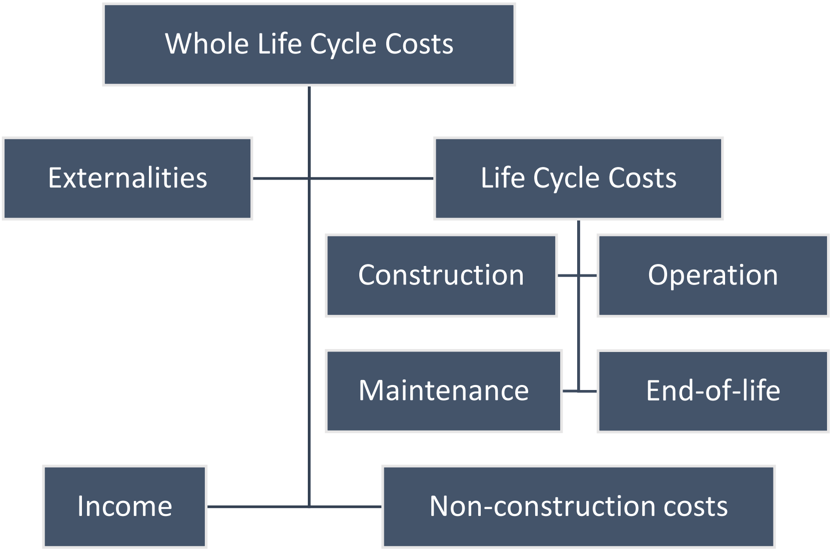


Figure 1 Whole Life Cycle Costs adapted from ISO 15686-5 (2017)

There are, however, a number of limitations of the suggested approaches to track substructure maintenance shown in Table 1. In particular, they do not consider all transport costs which, as well as future railway track infrastructure maintenance costs, should also take into account railway track use costs and mode change costs. Railway track use costs include rolling stock operation costs (i.e. fuel consumption and maintenance costs), capacity lost costs, accident costs and environmental impacts. Mode change costs are those associated with the change in use of rail compared to other modes (primarily road and air) due to track infrastructure investment. However, Whole Life Cycle Cost Analysis (WLCCA) approach requires predicting these future costs and benefits of railway track. For existing railway track in particular there is often a paucity of construction, condition and historical maintenance data. This makes future predictions of track deterioration, and therefore track condition and track use costs uncertain (Andrade, 2016; Asplund, 2016; Kirkwood et al., 2016; Andrews, 2012; Skinner et al., 2011). It is under conditions of uncertainty that decision makers must evaluate, compare and select among alternative strategies, the economically justifiable one. To address these issues, this paper describes a WLCCA approach under uncertainty to determine the most economically beneficial railway track substructure maintenance strategy for traditional ballasted railway track. To this end, the proposal approach provides railway policy and decision makers, for the first time, a means to appraise maintenance investment strategies by considering environmental, safety, social and economic costs and benefits.

Table 1 Overview of Life Cycle Costing Models for Railway Track and Rolling Stock

Author/Project	Description	Features considered within the model										WLCC Approach	Application				
		Asset Deterioration	Cost Elements														
			Design/Construction	Maintenance		Operation					End of Life						
				Track	Rolling Stock	Capacity Lost	Fuel / Energy	Environment	Risk of Accident	Socio-Economic Impacts			Track	Signaling	Electrification	Rolling Stock	Infrastructure
Lamson et al., (1983)	Proposed a method for application of decision network analysis to railway track maintenance and replacement optimization.	✓		✓									✓				
STAMP (2000)	Network Rail's single asset decision modelling tool to evaluate maintenance and renewal options for structural assets	✓		✓		✓						✓					✓
Zoeteman (2001)	A LCC approach to support decision-making system for design and maintenance decisions	✓	✓	✓		✓							✓				
Zhao et al., (2006)	Develops a LCC model for optimising railway ballast maintenance policies	✓		✓	✓	✓							✓				
Reddy et al., (2007)	Employs a LCC approach for optimising rail maintenance based on rolling contact fatigue, traffic wear, rail grinding interval and lubrication	✓		✓	✓	✓			✓				✓				
Antoni et al., (2008)	Developed statistical model to estimate lifetime and maintenance costs throughout life cycle of railway assets			✓		✓							✓	✓	✓		
Patra et al., (2009)	Presents a methodology for estimating uncertainty related to LCC within a developed track maintenance cost estimation model			✓		✓							✓				
INNOTRACK (2009)	The project aimed to develop a cost-effective high-performance track through reduced LCC and improved RAMS and developed various tools such as D-LCC, CATLOC, LCCWare etc.	✓	✓	✓		✓	✓	✓			✓		✓				
InfraCaLCC	A commercial software that calculates rail infrastructure LCC from the existing databases (MAINLINE, 2013)			✓		✓	✓	✓		✓	✓		✓				✓
De Jong et al., (2012)	An integrated LCC-SEC assessment approach proposed as part of Urban Track project to aid the development and construction of modular track systems for tram, metro and light rail.		✓	✓		✓		✓		✓	✓		✓				
VTISM	Integrates several models, i.e. VAMPIRE, WLRM, T-SPA, WPDM, and W-SPA to optimise rail and wheel life and maintenance regimes (Serco, 2013)	✓		✓	✓							✓	✓			✓	
Zhang et al., (2012)	A genetic algorithm approach for maintenance scheduling at a minimal overall cost	✓		✓		✓				✓			✓				
Mokrousov et al., (2013)	Developed a LCA method which can be applied to different rail elements	✓			✓						✓		✓	✓	✓	✓	✓

Author/Project	Description	Features considered within the model										WLCC Approach	Application				
		Asset Deterioration	Cost Elements														
			Design/Construction	Maintenance		Operation					End of Life						
				Track	Rolling Stock	Capacity Lost	Fuel / Energy	Environment	Risk of Accident	Socio-Economic Impacts			Track	Signaling	Electrification	Rolling Stock	Infrastructure
LCAT	Life Cycle Assessment Tool was developed as part of the MAINLINE (2013) project to reduce the economic and environmental impacts of maintenance, renewal and improvement of railway infrastructure	✓	✓	✓		✓		✓	✓	✓	✓	✓	✓				
Arasteh khouy et al., (2014)	Proposes optimization of track geometry inspection interval to minimize total ballast maintenance costs while considering risk of accidents due to poor track quality	✓		✓					✓				✓				
Caetano et al., (2014)	Introduced an optimization model to schedule track renewal operations using a LCC approach	✓		✓									✓				
Gattuso et al., (2014)	Proposes a set of cost functions for the estimation of regional railways investment and operating costs		✓	✓	✓			✓					✓	✓	✓	✓	
Zhang et al., (2014)	An approach combining expert knowledge and historical data, and cost modelling for maintenance strategy optimization	✓		✓									✓				✓
Banar et al., (2015)	LCA and LCC method to assess the environmental and economic impact on transportation systems		✓	✓	✓			✓		✓	✓		✓			✓	
Fang et al., (2015)	Model to predict LCC of maintenance strategies for rolling stocks		✓		✓											✓	
Zhang et al., (2015)	A LCC model for real-time condition monitoring in railways and metro systems under uncertainty approach	✓			✓	✓										✓	
Fourie et al., (2016)	Developed and tested a LCC framework for mission-critical assets with emphasis on cost of ownership and effective maintenance and renewal strategies	✓			✓		✓									✓	
Rama et al., (2016)	A modelling framework for evaluating multi-asset infrastructure LCC with a whole-system context	✓		✓	✓	✓							✓				✓
Jones et al., (2017)	A LCA approach to study the environmental impact of a high-speed rail			✓	✓			✓					✓			✓	
Smith et al., (2017)	A methodology to estimate the relative marginal cost of railway maintenance	✓		✓	✓								✓				
Vitasek et al., (2017)	A LCC method to optimise design of railroad switches			✓		✓					✓		✓				
Su et al., (2017)	A railway track maintenance optimisation approach considering uncertainty and train scheduling	✓		✓		✓							✓				
Su et al., (2019)	An optimisation approach of maintenance considering uncertainty and maintenance scheduling	✓		✓		✓							✓				

2. Total Transport Costs

This WLCCA model proposed considers the direct and indirect costs and benefits to all stakeholders (owners, operators, maintainers and users). The WLCC considered are those associated with ballasted track construction, maintenance, de-commissioning, track use, mode change and the environment. Together these are considered herein to represent total transport costs. Railway track maintenance and renewal costs are those to do with the direct costs to inspect, maintain and renew the railway track structure and the indirect costs associated with track maintenance such as delays, accidents and emissions (Andersson 2016 et al., 2016; ITF, 2013). Track use costs include train operation costs (i.e. the maintenance of rolling stock, fuel consumption and derailments), environmental costs and travel time. Mode change is associated with perceived change in socio-economic costs incurred by railway users. De-commissioning costs are associated with disposing of track assets at the end of their useful life.

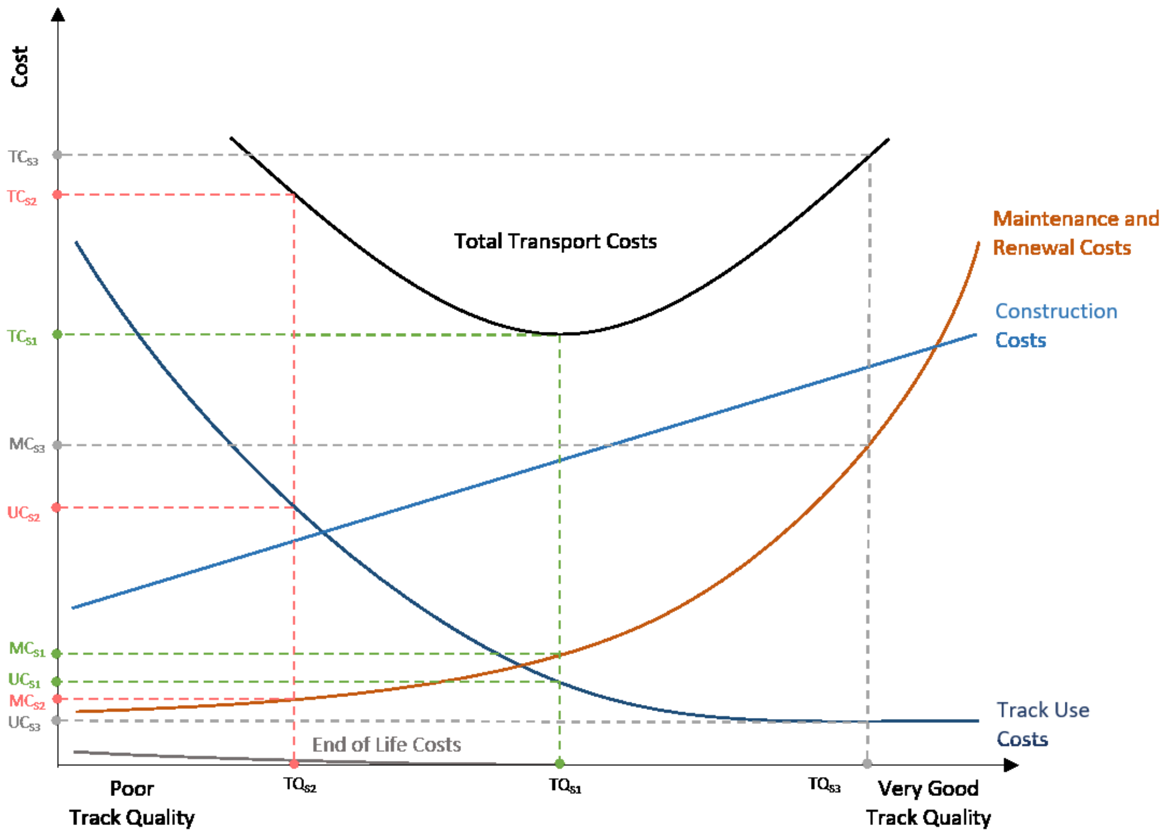


Figure 2 Optimal railway track maintenance standard

Figure 2 conceptualises the different cost elements that might occur within the life cycle of a section of railway track, as a function of the average track condition. Achieving a higher average track condition requires higher maintenance and construction costs. On the other hand, as track condition improves railway track use costs decrease non-linearly. The minimum total transport cost in Figure 2 (point TC_{S1}) yields the ideal average track condition TQ_{S1}, or optimal maintenance standard. Point MC_{S1} is the maintenance cost of achieving this standard. Achieving a track condition (TQ_{S2}), less than the ideal track condition, saves in maintenance costs (MC_{S2}) but results in an increase of railway track use costs (UC_{S2}). This increase in track use costs is greater than the savings in maintenance costs compared to the optimal maintenance standard (TQ_{S1}) and therefore results in higher total transport costs. On the other hand, a track condition, TQ_{S3}, greater than the ideal condition causes a reduced railway track use costs of UC_{S3} with an increase in maintenance costs (MC_{S3}). However, in this case the savings in track use costs compared to the increase in maintenance costs also result in higher total transport costs compared to the optimal maintenance standard.

3. Track deterioration and maintenance

For traditional ballasted railways, track geometry is used as a measure of the integrity of the track substructure, passenger comfort and the safety of train operation. It is also used by railway asset maintainers as the primary measure to trigger track substructure maintenance and renewal (M&R) activities (Guler et al., 2011; BSI, 2005). Furthermore, track use costs are also a function of track geometry (Zarembski et al., 2010). Consequently, for the research described herein the WLCC approach advocated uses track geometry as the sole measure of track condition. Maintenance intervention levels and track use costs therefore are assumed to be a function of track geometry (see Figure 3). Track geometry is usually described in terms of vertical and horizontal track geometry and it is normally measured using instrumented measuring trains (Guler, 2013; Jovanovic et al., 2011) at time intervals based on the traffic volume and the line speed (Prescott et al., 2013). The standard deviation of these measurements over a predetermined length (e.g. track sections of 200m length in the UK) is used in track maintenance standards to specify permissible deviations from the ideal.

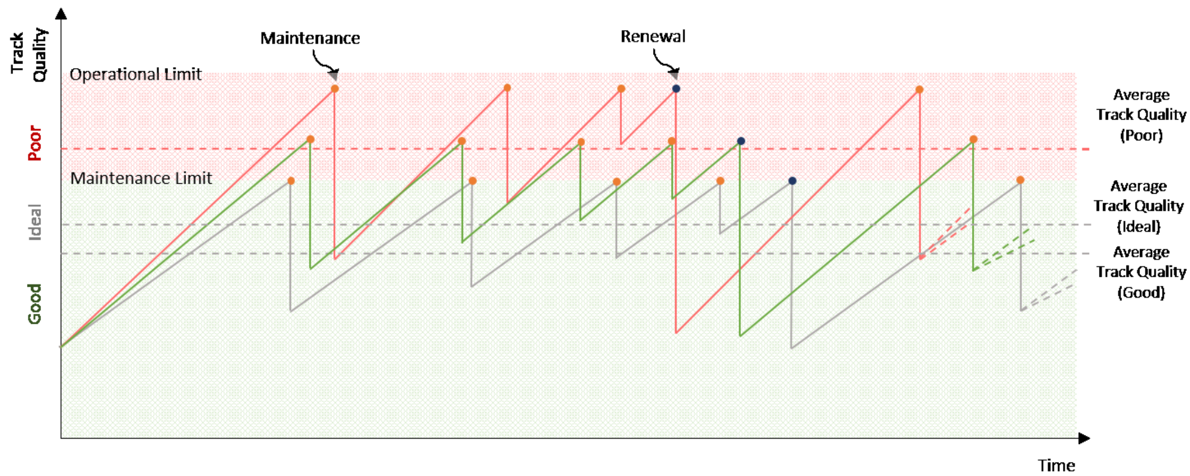


Figure 3 Track Geometry Deterioration

Over time, the combined damaging effects of rolling stock and the environment causes railway track geometry to worsen, necessitating track substructure maintenance. A variety of maintenance techniques are used depending on the component of the track substructure requiring maintenance. The most commonly used methods to correct vertical track geometry faults are tamping and stone blowing (Audley et al., 2013). These techniques are henceforth referred to as track realignment (Cellmer et al., 2016). Track realignment restores the track geometry by compacting the ballast under the sleepers, allowing the repositioning of the rails and sleepers. Poor track geometry coupled with the occurrence of fines within the ballast can necessitate ballast cleaning. The occurrence of fines within the ballast can be caused by ballast attrition resulting from loads imposed on the ballast by rolling stock, the upward migration of fines from the sub-ballast or subgrade, or the destructive effects of tamping on ballast particles during maintenance (Selig et al., 1994). Ballast attrition and the migration of fines are exacerbated by excessive dynamic train loads which can result from poor track or rolling stock condition (Burrow et al., 2017). The presence of fines within the ballast reduces interlocking between ballast particles and permeability, and therefore the ability of the ballast to carry train loads, subsequently affecting track geometry. Ballast cleaning removes the fine material and replaces the worn out ballast with fresh material. Eventually, when the ballast reaches the end of its useful life, it is replaced (i.e. renewed).

Track maintainers are therefore tasked with devising maintenance strategies which need to consider track deterioration rates, acceptable track geometry levels, and maintenance budgets, track down time and train schedules. Further, due to logistical constraints associated with budgets, machinery, human resources and the availability of the railway track, maintenance activities need to be planned at least one year in advance (Quiroga et al., 2011). Railway track maintenance is further complicated by the ever-increasing utilisation of railway networks and the pressure to make the railway continuously available, as mentioned above. Figure 3 shows how different maintenance strategies can result in different average track geometry values over time. Higher (worse) average track geometry values overtime result in higher railway track use costs. A challenge therefore when devising economic track maintenance strategies is to weigh the railway track inspection and maintenance costs required to keep the track to a given average value over time, against the associated railway track use costs.

4. Uncertainty

While employing WLCCA to aid decision making for railway track investments, there are some challenges concerning the lack of data associated with costs, benefits and the degradation rates of track infrastructure; giving rise to uncertainties (Andrade et al., 2016; Kirkwood et al., 2016; Skinner et al., 2011). Uncertainty can be defined as the chance of an event occurring where the probability distribution is unknown (Smith et al., 2006). Since the WLCCA approaches are based on the predictions of future scenarios, the sources of such uncertainty could also vary (see Figure 4) resulting in over-estimations or under-estimation of the WLCCA results. (Asplund et al., 2016).

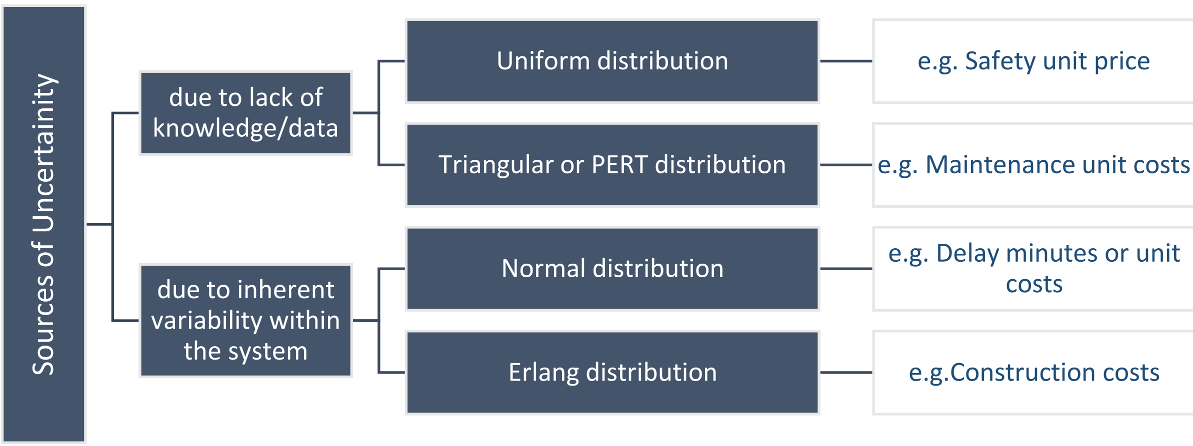


Figure 4 Sources of uncertainty and associated probability distributions for WLCCA adapted from Salling et al., (2011)

Risk assessment approaches such as Monte Carlo simulation, Bayesian, Fuzzy logic and Petri Nets are recommended to deal with such uncertainties (Zhang et al., 2014; Vogl, 2015; D. Rama et al., 2016). To a large extent, risk assessment techniques use historical data and probability judgements, and conclusions on the acceptability of solutions are often made directly based on derived probabilities. In many situations, it might also be extremely difficult to deal with uncertainty through probabilistic risk assessment, due to incomplete data (Sasidharan et al., 2017). The use of expert opinion is often suggested as a means of overcoming such issues (Terje, 2016; Torbaghan et al., 2015).

5. Proposed Model

An optimisation approach based on the concepts shown in Figure 2 requires consideration of a vast number of alternatives and is therefore computationally challenging. Therefore, the approach proposed uses WLCCA to compare railway track maintenance strategies to choose the most economically beneficial.

5.1. Whole Life Cycle Cost Analysis

The three most commonly used economic indicators to support decision making in transport investment appraisals are the Internal Rate of Return (IRR), the Benefit-Cost Ratio (BCR) and the Net Present Value (NPV) (Bristow et al., 2000). The IRR gives the rate of return on investments, or the discount rate at which the present-day values of benefits and costs are equal (Spiller, 2013). While comparing mutually exclusive investment options, the IRR may rank the options incorrectly if the time profile of benefits and costs differ (World Bank, 1998). The BCR is the ratio of benefits and costs expressed in present day values, with BCR ratios greater than one indicating economic viability. However, the BCR is often liable to misrepresentation due to its dependency on the degree of aggregation of benefits and costs over successive time periods.

The most widely used economic indicator for WLCCA is the Net Present Value (NPV) of current and future cost streams discounted to a reference time (Bristow et al., 2000) and it was therefore chosen for the task at hand. NPV is defined as follows (World Bank, 1998):

$$\widehat{NPV} = \sum_{\mathrm{n=0}}^{\mathrm{N}} \frac{(\widehat{\mathrm{B}}_n - \widehat{C_n})}{(1+\hat{r})^n} \tag{1}$$

ˆ is used to signify that the values are uncertain

Where the total transport cost, $\widehat{\mathrm{C}}_n$ during the year, *n*, of a railway track section to achieve an average track quality, *Q* may be calculated using Equation 2 as follows:

$$\widehat{\mathrm{C}}_n = \widehat{\mathrm{C}}_{\mathrm{Construction}(Q)_n} + \widehat{\mathrm{C}}_{\mathrm{Maintenance}(Q)_n} + \widehat{\mathrm{C}}_{\mathrm{Use}(Q)_n} + \widehat{\mathrm{C}}_{\mathrm{EndofLife}(Q)_n} \tag{2}$$

Where $\widehat{\mathrm{C}}_{\mathrm{Construction}(Q)_n}$, $\widehat{\mathrm{C}}_{\mathrm{Maintenance}(Q)_n}$, $\widehat{\mathrm{C}}_{\mathrm{Use}(Q)_n}$, $\widehat{\mathrm{C}}_{\mathrm{EndofLife}(Q)_n}$ are the costs for year, *n*, and average track quality, *Q*, with respect to the track construction, maintenance, use and end of life respectively. The terms are described in more detail below.

5.1.1. Construction Cost

The cost of construction is made up of costs associated with acquiring land and employing staff, procurement of materials and deployment of machinery of type, *m*. $\hat{\mathrm{C}}_{\mathrm{Construction}(Q)n}$ given by Equation 3, is the discounted cost to construct a railway track of length *L*.

$$\hat{\mathrm{C}}_{\mathrm{Construction}(Q)n} = \left(\hat{C}_{Prop} * L\right) + \sum_{m=1}^{M} \left[\left(\hat{C}_{Emn} * \hat{E}_{mn}\right) + \left(\hat{C}_{Cmn} * L\right)\right] \tag{3}$$

5.1.2. Maintenance costs

The direct and indirect costs associated with ballasted railway track maintenance are the sum of the costs of inspection ($\hat{\mathrm{C}}_{\mathrm{INS}}$), track realignment ($\hat{\mathrm{C}}_{\mathrm{TRA}}$), ballast cleaning ($\hat{\mathrm{C}}_{\mathrm{BC}}$), ballast renewal ($\hat{\mathrm{C}}_{\mathrm{BR}}$), routine maintenance ($\hat{\mathrm{C}}_{\mathrm{RM}}$), delays ($\hat{\mathrm{C}}_{\mathrm{CL}}$) and spillage ($\hat{\mathrm{C}}_{\mathrm{SPL}}$), as expressed in Equation 4.

$$\hat{\mathrm{C}}_{\mathrm{Maintenance}(Q)n} = \hat{\mathrm{C}}_{\mathrm{INS}_n} + \hat{\mathrm{C}}_{\mathrm{TRA}_n} + \hat{\mathrm{C}}_{\mathrm{BC}_n} + \hat{\mathrm{C}}_{\mathrm{BR}_n} + \hat{\mathrm{C}}_{\mathrm{RM}_n} + \hat{\mathrm{C}}_{\mathrm{CL}_n} + \hat{\mathrm{C}}_{\mathrm{SPL}_n} \tag{4}$$

The different cost elements that contribute to the maintenance costs of the ballasted track are calculated using Equations 5-11.

Track Inspection Cost

Track inspection is carried out periodically to assess the condition of the infrastructure. Track inspection costs depend upon the frequency of the inspections, *u*, in a year and the deployment of different types of equipment of type, *m*. The costs, are calculated via Equation 5.

$$\hat{\mathrm{C}}_{\mathrm{INS}_n} = \sum_{u=1}^{U} \sum_{m=1}^{M} \left(\hat{C}_{Emn} * \hat{E}_{mn} + \hat{C}_{TImn}\right) * L \tag{5}$$

Track Realignment Costs

Track realignment costs are a function of the number of times, *u*, the maintenance activity is carried out in a given year and on the deployment of the required machinery of type, *m*. Realignment costs are determined using Equation 6.

$$\hat{\mathrm{C}}_{\mathrm{TRA}_n} = \sum_{u=1}^{U} \sum_{m=1}^{M} \left(\hat{C}_{Emn} * \hat{E}_{mn} + \hat{C}_{TRAmn}\right) * L \tag{6}$$

Ballast Cleaning Cost

The cost of ballast cleaning is a function of the number of times ballast cleaning takes place in a year, *u*, and the deployment of the required machinery of type, *m*. Ballast cleaning costs are determined using Equation 7.

$$\hat{\mathrm{C}}_{\mathrm{BC}_n} = \sum_{u=1}^{U} \sum_{m=1}^{M} \left(\hat{C}_{Emn} * \hat{E}_{mn} + \hat{C}_{BCmn} + \hat{C}_{B}\right) * L \tag{7}$$

Ballast Renewal Cost

The costs incurred due to ballast renewal are a function of the number of ballast renewals, *u*, carried out in year *n* and the deployment of machinery of type, *m*. The costs are calculated using Equation 8.

$$\hat{\mathrm{C}}_{\mathrm{BR}_n} = \sum_{u=1}^{U} \sum_{m=1}^{M} \left(\hat{C}_{B} + \hat{C}_{Emn} * \hat{E}_{mn} + \hat{C}_{BRmn}\right) * L \tag{8}$$

Routine Maintenance Costs

Activities such as weed spraying, vegetation removal and drainage cleaning are considered as routine maintenance activities. Routine maintenance costs are calculated using Equation 9 as a function of the number of such activities in a year *u*, and the deployment of machinery type, *m*.

$$\hat{C}_{\mathrm{RM}_n} = \sum_{u=1}^{U} \sum_{m=1}^{M} (\hat{C}_{Emn} * \hat{E}_{mn} + \hat{C}_{RMmn}) * L \tag{9}$$

Capacity Cost

The capacity loss costs are those associated with speed restrictions, disruptions and maintenance activities. Speed restrictions on the railway are required when the track quality exceeds safety values specified in maintenance standards (see Figure 3), and result in travel time delays. Unplanned, or maintenance which over runs, can cause disruptions and or cancellations to services. Assuming that the number of train services remain the same during period, *n*, capacity loss cost is calculated using Equation 10.

$$\hat{C}_{\mathrm{CL}_n} = \left[\hat{C}_{PDn} * \left(\frac{L}{S_{RP}} - \frac{L}{S_L}\right) * \hat{N}_{PTSRn}\right] + \left[\hat{C}_{FDn} * \left(\frac{L}{S_{RF}} - \frac{L}{S_L}\right) * \hat{N}_{FTSRn}\right] + \left(\hat{C}_{PDn} * \hat{N}_{PTDn} * \hat{T}_{APDMn}\right) + \left(\hat{C}_{FDn} * \hat{N}_{FTDn} * \hat{T}_{AFDMn}\right) \tag{10}$$

Spillage Cost

These costs are to do with the clean-up using machinery type, *m*, train delays and reduced service life of a track section on the plain line, due to the spillage of materials such as fuel, coal and chemicals. Spillage costs are determined using Equation 11.

$$\hat{C}_{\mathrm{SPL}_n} = \left[\sum_{m=1}^{M}\left(\hat{C}_{Emn} * \hat{E}_{mn} * L\right) + (\hat{C}_{CSmn} * L)\right] + (\hat{C}_{PDn} * \hat{N}_{PTDn} * \hat{T}_{APDMn}) + (\hat{C}_{FDn} * \hat{N}_{FTDn} * \hat{T}_{AFDMn}) + (\hat{T}_{RSLn} * \hat{C}_{RSLn}) \tag{11}$$

5.1.3. Track use costs

The discounted railway track use costs, $\hat{C}_{\mathrm{Use}(Q)_n}$, for the year, *n*, for an average track quality, Q_A, are associated with train operation ($\hat{C}_{\mathrm{TO}_n}$), derailments ($\hat{C}_{\mathrm{DR}_n}$), environmental impacts ($\hat{C}_{\mathrm{ENV}_n}$) and modal change benefits ($\hat{C}_{\mathrm{MCC}_n}$). They are calculated using Equation 12.

$$\hat{C}_{\mathrm{Use}(Q)_n} = \hat{C}_{\mathrm{TO}_n} + \hat{C}_{\mathrm{DR}_n} + \hat{C}_{\mathrm{ENV}_n} - \hat{C}_{\mathrm{MCC}_n} \tag{12}$$

Train Operating Cost

The train operating costs considered are the costs associated with rolling stock fuel consumption, maintenance and replacement of spare parts of vehicle type, *v*, and are expressed by Equation 13.

$$\hat{C}_{\mathrm{TO}_n} = \sum_{v=1}^{V}(((\hat{F}_{CPnV(Q)} * \hat{C}_{FPnV} * L) + \left(\hat{N}_{TSPnV(Q)} * \hat{C}_{TSPnV(Q)}\right) + \hat{C}_{TMPnV(Q)}) * \hat{N}_{PnV}) + ((\hat{F}_{CFnV(Q)} * \hat{C}_{FFnV} * L) + \left(\hat{N}_{TSFnV(Q)} * \hat{C}_{TSFnV(Q)}\right) + \hat{C}_{TMFnV(Q)}) * \hat{N}_{FnV}) \tag{13}$$

Risk of Derailment Cost

The cost of derailments is estimated by multiplying the average cost of a derailment (C_{DQ}) with the probability of occurrence of a derailment (P_{DQ}) during the analysis period (Equation 14). The cost components of a derailment include damage to third party property and passengers' health, loss of life, damage to goods and costs involved in rescue, delays, investigation and repair and renewal of track and rolling stock.

$$\hat{\mathrm{C}}_{\mathrm{DR}_n} = P_{DQ} * \hat{C}_{DQ} \tag{14}$$

Environmental Cost

The environmental costs incurred due to pollutant type, *p*, during construction ($\hat{E}_{pCn}$), maintenance ($\hat{E}_{pMn}$) and renewal ($\hat{E}_{pRn}$), operation ($\hat{E}_{pOn}$) and disposal ($\hat{E}_{pDn}$) during year, *n*, are determined using Equation 15 as follows:

$$\hat{\mathrm{C}}_{\mathrm{ENV}_n} = \sum_{p=1}^{P} (\hat{E}_{pCn} + \hat{E}_{pMn} + \hat{E}_{pRn} + \hat{E}_{pOn} + \hat{E}_{pDn}) * \hat{C}_{pIn} \tag{15}$$

Mode Change Benefit

Improved track condition enhances the journey quality and safety, which in turn encourages users to shift from other modes of transportation to railways (Lingaitis, 2014). The costs taken into account in this work from such a shift are changes in travel times, reduced road congestion and road accidents and associated environmental costs. The mode change cost is determined using Equation 16.

$$\hat{\mathrm{C}}_{\mathrm{MCC}_n} = \left(\hat{N}_{PSQ} * \hat{C}_{PS}\right) + \left(\hat{N}_{FSQ} * \hat{C}_{FS}\right) + \left(\hat{N}_{ARS} * \widehat{VOL}\right) + \hat{C}_{EnvImp} \tag{16}$$

5.1.4. End of Life costs

For a section of track of length, L, the costs incurred to dispose of, or recycle, each track asset, *x*, at the end of the useful life of the asset, is given by Equation 17.

$$\hat{\mathrm{C}}_{\mathrm{EndofLife}(Q)_n} = \sum_{x=1}^{X} \sum_{m=1}^{M} \left(\hat{C}_{Emn} * \hat{E}_{mn} * L\right) + \left(\hat{C}_{EOImx} * L\right) - Rav \tag{17}$$

5.2. Track deterioration modelling

A number of the cost components and the timing of maintenance in Equations 7-11 are a function of the railway track condition (as measured by track geometry). Consequently, the WLCCA approach advocated requires both the future condition of the railway track and the effectiveness of track maintenance to be established (see Figure 3). Table 2 summarises from the literature a number of the track deterioration models which could be used for this purpose. Most of these models predicts vertical track settlement as a function of number of repetitions of train load. In some cases, train speed and the effectiveness of maintenance are also considered.

Table 2 Track Deterioration Models

Country	Model name	Equation	Influencing Factors
UK	Shenton (1985)	$S = K_s \frac{A_e}{20}(0.69 + 0.028L)N^{0.2} + 2.7 \times 10^{-6}N)$	*S* - track settlement K_s - structure factor A_e - equivalent axle load *N* - cumulative number of axles *L* - Lift given by tamping machines
Germany	DSM (Milosavljevic et al., 2012)	$S = S_1(1 + K_H \ln N)$	S_1 - initial settlement after first loading cycle K_H - coefficient*
Japan	Hoshino (Milosavljevic et al., 2012)	$\Delta = L_H.J.Z$	*Δ* - coefficient of track deterioration L_H - load factor *J* - structure factor *Z* - condition factor
	Sugiyama (2007)	$Z = 2.09 \times 10^{-3}.\ T^{0.31}.V^{0.98}.J^{1.10}.R^{0.21}.K_p^{0.26}$	*Z* - average growth of track irregularities in the section *T* - cumulative tonnage *V* - average running speed *J* - structure factor *R* - influence factor for jointed rail K_p - influence factor for subgrade
	Sato (1997)	$BS = \begin{cases} a_s(p_b - p_{g.br})^w, p_b > p_{g.br} \\ 0, p_b \leq p_{g.br} \end{cases}$ $BS = \alpha_s.p_b^w$	*BS* - ballast settlement a_s, α_s - coefficients* p_b - sleeper-ballast contact pressure $p_{b.gr}$ - threshold limit value of sleeper-ballast contact pressure *w* - exponent*
France	Guérin (1996)	$\frac{dS}{dN} = \alpha_G.y^{\beta_G}$	*y* - maximum elastic deflection during a loading cycle α_G, β_G - material parameters
South Africa	Frohling (1998)	$S = \left[\left[K_{F1} + K_{F2}.\left(\frac{D_{2mi}}{K_{F3}}\right)\right]\frac{Q_{tot}}{Q_{ref}}\right]^w \log N$	D_{2mi} - measured track stiffness at a particular sleeper i K_{F1}, K_{F2}, K_{F3} – settlement constants* Q_{tot} - prevailing wheel load Q_{ref} - reference wheel load *w* - exponent*
	Exponential (Quiroga et al., 2010)	$TQ_m = Ae^{B(x-x_o)}$	*TQ_m - track quality measure* *A, B - exponential coefficients* *x*, x_0 - time or tonnage
	Linear (Soleimanmeigouni et al., 2018)	$TQ_m = (a.x) + b$	TQ_m - track quality measure *x* - time or tonnage *a, b* - linear coefficients*

** - coefficients whose values depend on local conditions and are determined empirically*

6. Case Studies

The proposed WLCCA approach was used to calculate the NPV for the maintenance strategies outlined in Table 3 for representative sections of three different routes on the UK mainline railway network. A 25-year period of analysis and a discount rate of 3.5% were used in in accordance with UK Department for Transport (DfT, 2004) guidelines. The three selected routes are a commuter route (route 1), a high-speed passenger (route 2), and a mixed passenger-freight (route 3). The high-speed passenger route runs from London (LDN) to Birmingham (BHM) for 160 km (100 miles) via Coventry (COV). From Coventry onwards, it operates as a mixed passenger-freight route for 27 km (17 miles). The commuter route chosen is a 51 km (32 miles) long route in the Midlands running from Sutton Coldfield (SUT) to Lichfield City (LIC). All three train routes have competing road transport (see Table 4), but not competing canal, sea or air routes. For each route, a 200m long track representative section of homogenous construction, maintenance and renewal history, and social and economic geography were identified and used for the analysis.

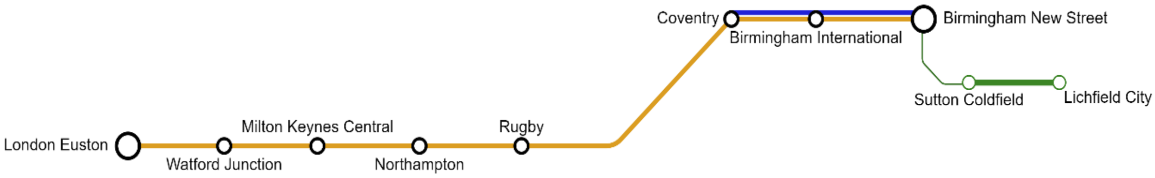


Figure 5 Routes selected for Case Study

The track geometry conditions and the effect of track realignment on track condition were determined from historical track data using a linear regression model of the form which has been used successfully to accurately model railway track degradation (see for example Soleimanmeigouni et al., 2018; Andrade et al., 2011; Faiz et al., 2009) (see Table 2). Monte Carlo Simulation (MCS) was used to analyse the historical track condition measurements in order to identify the most probable track condition for the representative section following maintenance. This approach followed that suggested by Quiroga et al. (2010).

The Table 3 shows the track maintenance strategies considered to achieve a given average track quality. For all the strategies track renewal takes place when track realignment is insufficient to achieve the given average track quality. Ballast cleaning was not considered due to the lack of available data. For the three representative sections the do-minimum strategies are 3.6 mm, 3.0 mm and 2.7 mm respectively. In order to realise different average track qualities, the time interval between consecutive track realignment activities were delayed until a renewal is necessitated. The annual average track quality was used to inform the annual track use costs determined using equations 12 to 16.

The data required for the WLCCA was obtained from a variety of sources and is presented in Table 4. In order to address possible uncertainties with the data used to calculate the impacts and benefits, Monte Carlo Simulation was used to calculate a probability distribution for each input data value. In each case a normal distribution was assumed and determined using three-point following the approach suggested by Elcheikh et al., (2016). The three-point estimates were obtained from the sources listed in Table 4. The Monte Carlo Simulation was performed for 10,000 iterations using the @RISK^{TM} software (Pallisade, 2017) to calculate the NPV and total transport costs for the maintenance strategies considered.

Table 3 Maintenance strategies adopted for the Case Studies

Route	Average Track Quality (in SD mm)	Year																								
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Sutton Coldfield-Lichfield City	2.4		TRA		TRA		BR	TRA		TRA			TRA		TRA		BR	TRA		TRA			TRA		TRA	
	2.5		TRA		TRA		BR		TRA		TRA		TRA		TRA		BR		TRA		TRA		TRA		TRA	
	2.6			TRA			BR			TRA				TRA			BR			TRA				TRA		
	2.7				TRA		BR				TRA				TRA		BR				TRA				TRA	
	2.9					TRA		BR								TRA		BR								TRA
	3.1					TRA			BR							TRA			BR							TRA
	3.4							TRA			BR							TRA			BR					
	3.5							TRA			BR								TRA		BR					
	3.6								TRA		BR								TRA		BR					
London Euston-Birmingham New Street	1.9		TRA	TRA	TRA		TRA	TRA		TRA	BR		TRA	TRA	TRA		TRA	TRA		TRA	BR		TRA	TRA	TRA	
	2.2		TRA		TRA		TRA		TRA	TRA	BR		TRA		TRA		TRA		TRA	TRA	BR		TRA		TRA	
	2.4			TRA		TRA		TRA		TRA	BR			TRA		TRA		TRA		TRA	BR			TRA		TRA
	2.5				TRA		TRA		TRA		TRA	BR			TRA		TRA		TRA		TRA	BR			TRA	
	2.6					TRA		TRA		TRA	BR					TRA		TRA		TRA	BR					TRA
	2.7			TRA			TRA		TRA		BR			TRA			TRA		TRA		BR			TRA		
	2.8			TRA				TRA			BR			TRA				TRA			BR			TRA		
	2.9								TRA		BR								TRA		BR					
	3.0									TRA		BR								TRA		BR				
Coventry-Birmingham	1.2	TRA	TRA	BR		TRA	TRA		TRA	BR	TRA	TRA	TRA	BR		TRA	TRA		TRA	BR	TRA	TRA	TRA	BR		TRA
	1.4	TRA	TRA	TRA		TRA	TRA	TRA		TRA	T B	TRA	TRA	TRA		TRA	TRA	TRA		TRA	T B	TRA	TRA	TRA		TRA
	1.6		TRA	TRA	TRA		TRA	TRA		TRA	BR		TRA	TRA	TRA		TRA	TRA		TRA	BR		TRA	TRA	TRA	
	1.9		TRA		TRA		TRA		TRA		T B		TRA		TRA		TRA		TRA		T B		TRA		TRA	
	2.1		TRA		TRA			TRA		TRA	BR		TRA		TRA			TRA		TRA	BR		TRA		TRA	
	2.3			TRA			TRA		TRA		BR			TRA			TRA		TRA		BR			TRA		
	2.4			TRA			TRA				T B			TRA				TRA			T B			TRA		
	2.5				TRA					TRA	T B				TRA				TRA		T B				TRA	
	2.6								TRA	TRA	BR								TRA	TRA	BR					
	2.7								TRA		BR								TRA		BR					

TRA/T	Track Realignment
BR/B	Ballast Renewal

Table 4 Data used for Case Study

Item	Cost (£ per unit)			Source	Notes
	Minimum	Maximum	Most-Likely		
Inspection	£14,000/shift	£16,000/shift	£15,000/shift	Data collected from Network Rail	The cost is related to High speed track recording coach (HSTRC) used by NR to measure periodically track geometry. The cost includes both the cost of operating the HSTRC and employee costs. For the three routes considered the HSTRC is used to inspect the track geometry every 8-10 weeks. A shift equates to measuring 250 km of track (ORR, 2012). For the purpose of this research it was therefore assumed that an inspection was carried out on average every 8 weeks. Manual inspections carried out (e.g. earthworks/ drainage) and ad hoc track structural condition assessments were not considered.
Track Realignment	£4,500/shift	£5,500/shift	£5,000/shift		The cost is related to operating the track treatment fleet and the associated employee costs. NR often operates the track treatment fleet during the night time and maintains approximately 100m of track during one shift (ORR, 2012)
Ballast Renewal with new components	£900,000/km	£1,100,000/km	£1,000,000/km		The cost is related to operating the High Output Track Renewal System (HOTRS) used by NR for replacing the ballast, which is usually carried out overnight. The 800m long HOTRS is operated across all the routes considered, while the cost associated with it depends upon type of ballast renewal requirement (i.e. including or excluding formation renewal)
Ballast Cleaning	£7,500/shift	£12,500/shift	£10,000/shift		The cost is related to the operation of the High Output Ballast Cleaning System (HOBCS) and associated employee costs. The half-a-mile long HOBCS is operated by NR to clean the ballast and replace any poor-quality ballast. HOBCS cleans approximately 100 meters of track during a shift.
Routine Maintenance	£7,500/shift	£12,500/shift	£10,000/shift		The cost involved is associated with carrying out various activities such a weed spraying, vegetation removal and drainage cleaning, both manually and using machines.
Delay penalties on routes with low importance	£30/min/train	£70/min/train	£50/min/train		The commuter route selected is classified as a low importance route with approximately 40% of WMT services running a minimum 10 minutes late, with track related delay accounting for approximately 7% of the delayed services (ORR, 2018)
Delay penalties on routes with high importance	£210/min/train	£290/min/train	£250/min/train		Both the high-speed passenger route & the mixed passenger-freight route are of high importance, with approximately 60% of VWC services running minimum 10 minutes late, with track related delay accounting for approximately 9.5% of those delayed services (ORR, 2018). 2/10 freight services on UK mainline networks are delayed (NR,2010)

Spillage	£2000/mile/year	£2300/mile/year	£2100/mile/year	ORR (2013)	NR carries out both machine and manual interventions on the freight lines to treat spillages on the track. NR estimates that the coal spillage reduces the service life of the track by 9%.
Cost of track quality related derailment	£461,000/derailment	£761,000/derailment	£661,000/derailment	RSSB (2016)	
Environmental impact due to transport related NoX emissions in: Central London area Urban Large area Urban Small area	£46,162/tonne £14,647/tonne £7,273/tonne	£184,648/tonne £58,587/tonne £29,091/tonne	£115,405/tonne £36,617/tonne £18,182/tonne	DEFRA (2015)	The quantities of NoX and SO2 emissions for Class 390 and Class 323 fleets were adopted from AEA (2007)
Environmental Damage due to Transport related SO_2 emissions	£1,581/tonne	£2,224/tonne	£1,956/tonne	DEFRA (2015)	
Environmental Damage due to Transport related CO_2 emissions	£3.97 - £60.52 /tonne	£5.94 - £183.10 /tonne	£3.82 - £132.12 /tonne	AEA (2008) BEIS (2018)	The quantity of CO_2 emissions were assumed to be proportional to the fuel consumption and was calculated using the methodology specified by AEA (2008). CO_2 impact costs varies for each year and BEIS (2018) forecasts these costs
Road de-congestion (passenger service)	£0.15/vehicle mile	£0.17/vehicle mile	£0.16/vehicle mile	UIC (2015)	DfT Road Count Point data (DfT, 2018) were used to calculate the daily average number of passenger vehicles for the major road alternatives for each train routes. i.e. 40,000, 30,000 and 8,330 on M40 (LDN_BHM)), A45 (COV-BHM)) and A5127 (SUT-LIC)) roads respectively. Similarly, 1,825 freight vehicles were estimated to use the A45. For illustrative purposes, it was assumed that 10% of current road users using the alternative road route will shift to rail when the track is maintained in good track condition and reduce linearly to 0% when the track is maintained in poor condition; as suggested by Kemp (2016).
Reduction of road accidents (passenger service)	£0.02/vehicle mile	£0.04/vehicle mile	£0.03/vehicle mile		
Environmental benefits (passenger service)	£0/vehicle mile	£0.02/vehicle mile	£0.01/vehicle mile		
Modal Change Cost for passenger services	£0.10/vehicle mile	£0.30/vehicle mile	£0.20/vehicle mile	DfT (2011)	
Modal Change Cost for freight services	£0.40/vehicle mile	£0.60/vehicle mile	£0.50/vehicle mile	DfT (2011)	
Train Operating Cost on London-Birmingham route	£3.14/mile/train	£3.34/mile/train	£3.24/mile/train	ORR (2015)	The costs related with train operation is associated with staff, fuel, maintenance of rolling stock and the charges payable by the TOCs to Network Rail. VWC runs 51 passenger daily services on Class 390 fleets. WMT runs 96 passenger daily services on Class 323 fleets
Train Operating Cost on Sutton Coldfied-Lichfield city route	£3.92/mile/train	£4.12/mile/train	£4.02/mile/train		
Freight Train Operating Cost on Coventry-Birmingham route	£3.78/mile/train	£3.98/mile/train	£3.88/mile/train	Serco (2013)	4 daily average freight services are run on mixed-freight route (ORR, 2015). The operational costs of freight services are up to 20% more than their passenger counterparts (Serco, 2013).
Fuel Costs for London-Birmingham route (passenger service)	£17.53/kWh/mile	£31.56/kWh/mile	£24.55/kWh/mile	Data collected from Network Rail	The fuel consumed by the fleets used on each route were adapted from Network Rail's prediction data. The energy loss in the train suspension system increases exponentially as a function of the track geometry condition as suggested by Zarembski et. al., (2010).
Fuel Costs for Sutton Coldfield-Lichfield route (passenger service)	£4.33/kWh/mile	£7.80/kWh/mile	£6.07/kWh/mile		
Fuel Costs for Coventry-Birmingham route (freight service)	£0.20/litre	£0.40/litre	£0.30/litre		
Risk of track quality related derailments	0.03 FWI/year	0.23 FWI/year	0.13 FWI/year	RSSB (2018)	Based on the analysis of derailment data from the UK's Train Accident Precursor Indicator Model, the frequency of occurrence was assumed to follow a Poisson's distribution

6.1. Results

The plausible ranges of NPV and total transport costs determined from the Monte Carlo Simulation for the three representative track sections are presented in Figures 6a-6e, 7a-7e and 8a-8e respectively as a function of track quality. The figures show the minimum, mean and maximum values of costs associated with WLCC and the NPV at confidence levels of 10% - 90%. The range of plausible values provides the decision maker with an effective insight into the variability of the associated costs i.e. the uncertainty associated within the WLCCA. The results from the WLCCA shows that for all three routes, higher average track quality levels result in higher maintenance costs and lower track use costs, as would be expected. The contribution of different cost elements for all three total transport costs across all three routes are presented in Figures 9a-9c.

From Figures 6a and 6b it can be seen that maintaining the commuter route at an average track condition of 2.6 mm is the most economical of those strategies considered. At the 90% confidence level, the strategy results in an NPV of -£2.36 m and a lowest total transport cost of £2.95m with associated maintenance and track use costs of £1.1m and £1.2m respectively (see Figures 6d-6e). By contrast, the do-minimum strategy of maintaining the track condition at 3.6mm SD would result in a 25% increase in track use costs, at least a 75% increase in risk cost of derailments and a 60% less benefit from mode change at the 90% confidence level. Track maintenance costs however would reduce by approximately 50% (see Figure 6d).

Figures 7a and 7b shows that maintaining the high-speed passenger section at an average track condition of 2.4 mm SD is the most economic strategy. This strategy, at the 90% confidence level, has an NPV of -3.26m, a total transport cost of £4.62m with a maintenance cost of £1.3m. The do-minimum strategy, on the other hand, although it reduces maintenance costs by approximately 20%, results in an increase of track use costs of about 33% (Figures 7d-7e). The do-minimum strategy also increases derailment risk costs and train operation costs by 60% and 3% respectively. A strategy of maintaining a higher average track condition of 1.9mm, compared to the most economic strategy yields a 6% lower NPV and reduced track use costs of approximately 2% at the 90% confidence level. However, the more frequent intervention results in an 11% increase in maintenance costs.

The most economic strategy for the mixed-traffic section is to maintain the section at an average track condition of 2.4 mm (see Figure 8a). At the 90% confidence level this will result in an NPV which is 13% lower than the do-minimum strategy and a total transport costs of £4.2m, the lowest of all strategies considered (see Figures 8a-8b). By comparison, maintaining the track at 1.4mm, at the 90% confidence level, would reduce the NPV by 16%, but would increase total transport costs by 14% (see Figures 8a-8b). The more frequent maintenance requirements of the latter strategy result in maintenance costs which are 60% higher than the most economic strategy.

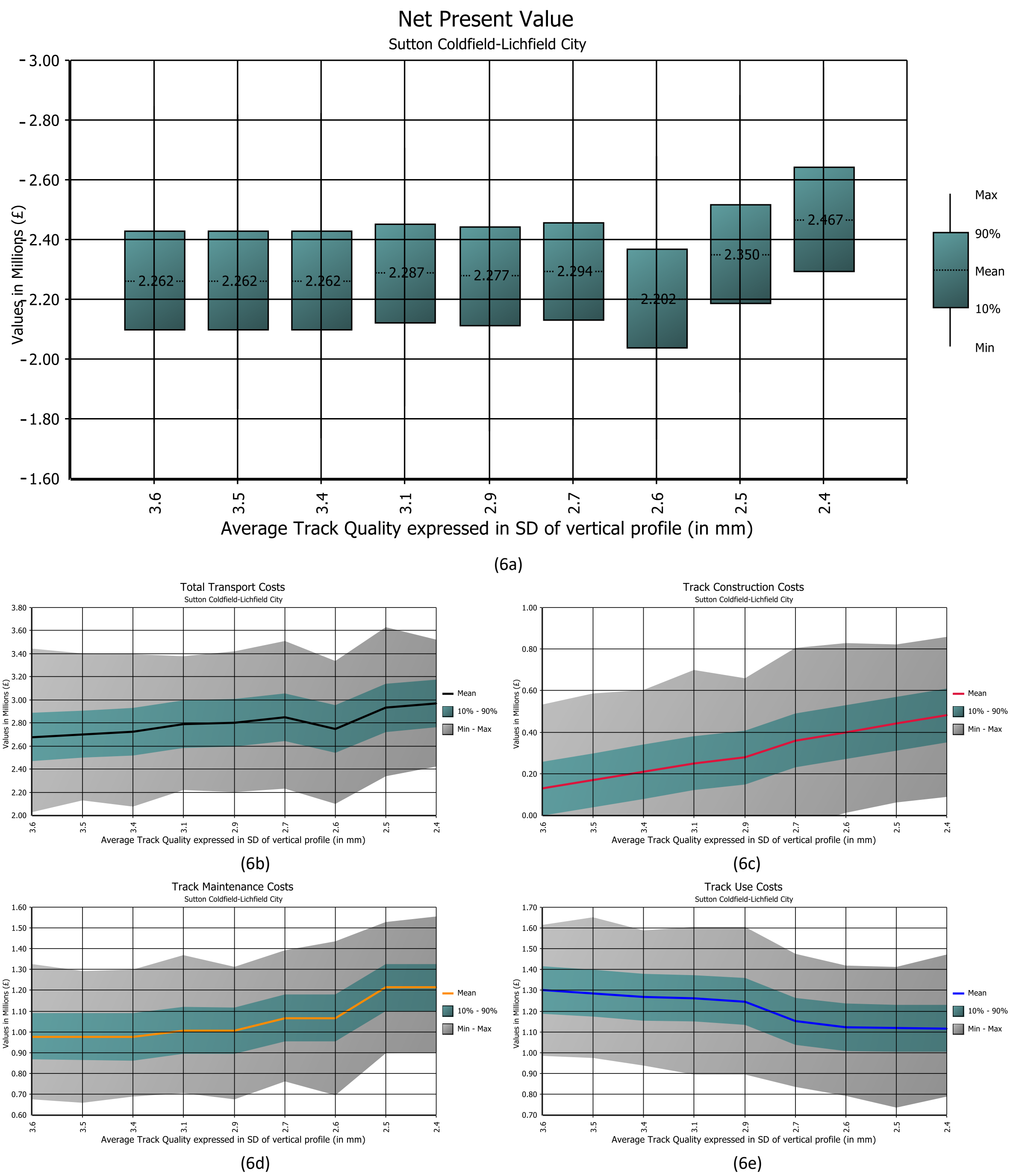


Figure 6 WLCCA results for Commuter Route with (a) NPV (b) Total Transport Cost (c) Construction Costs (d) Maintenance Costs and (e) Track Use Costs as a function of average Track Quality

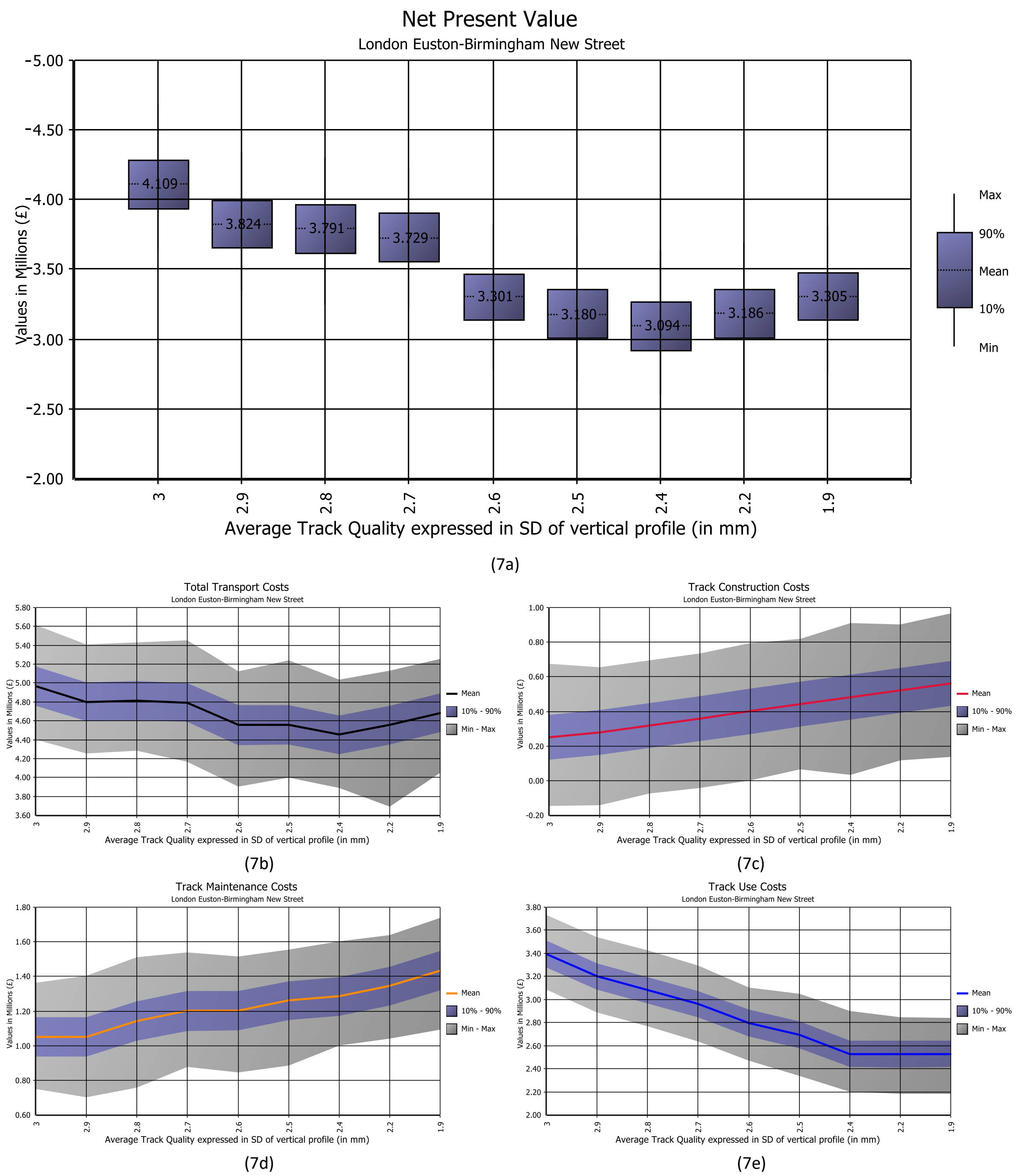


Figure 7 WLCCA results for High-Speed Passenger Route with (a) NPV (b) Total Transport Cost (c) Construction Costs (d) Maintenance Costs and (e) Track Use Costs as a function of average Track Quality

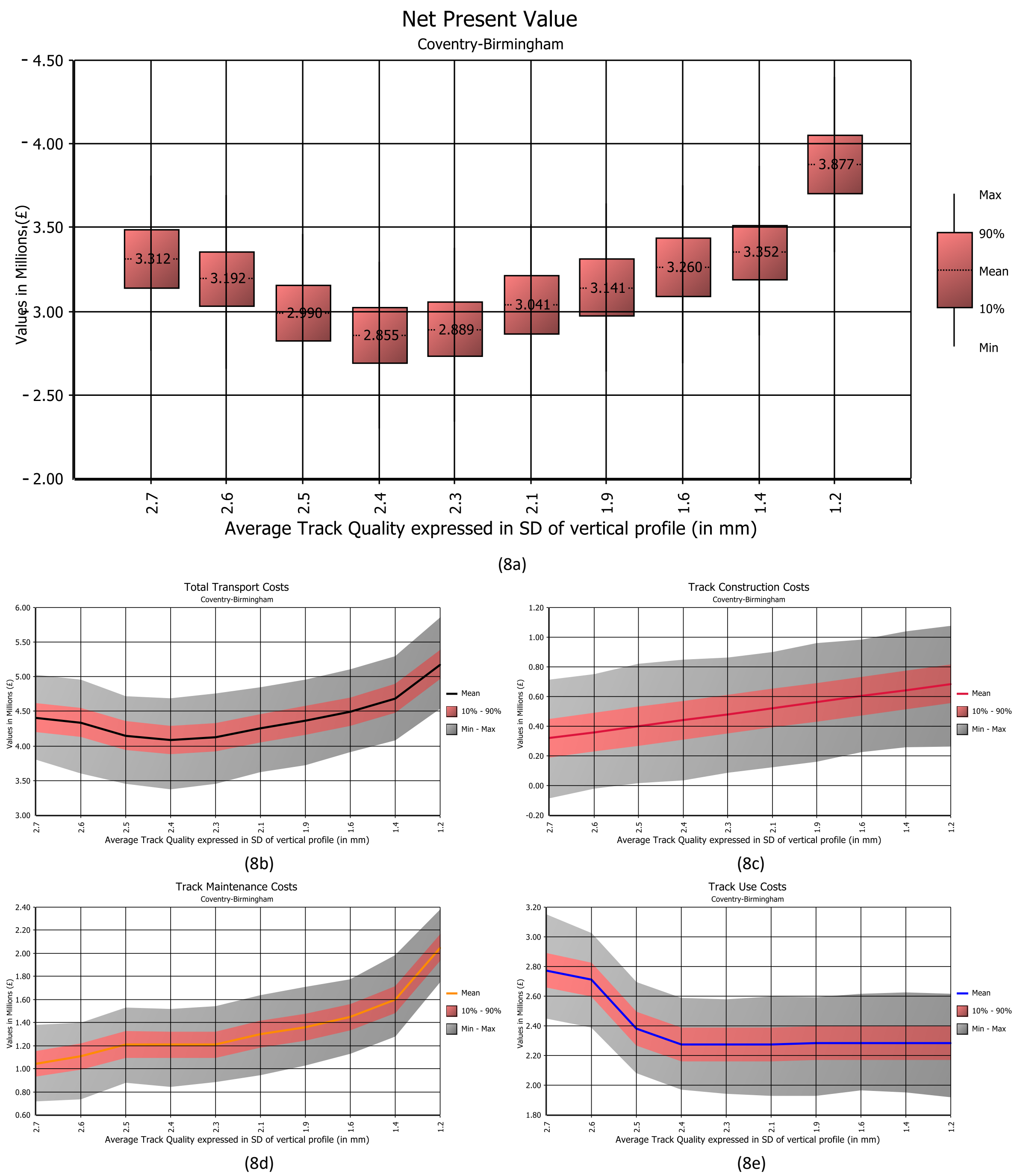
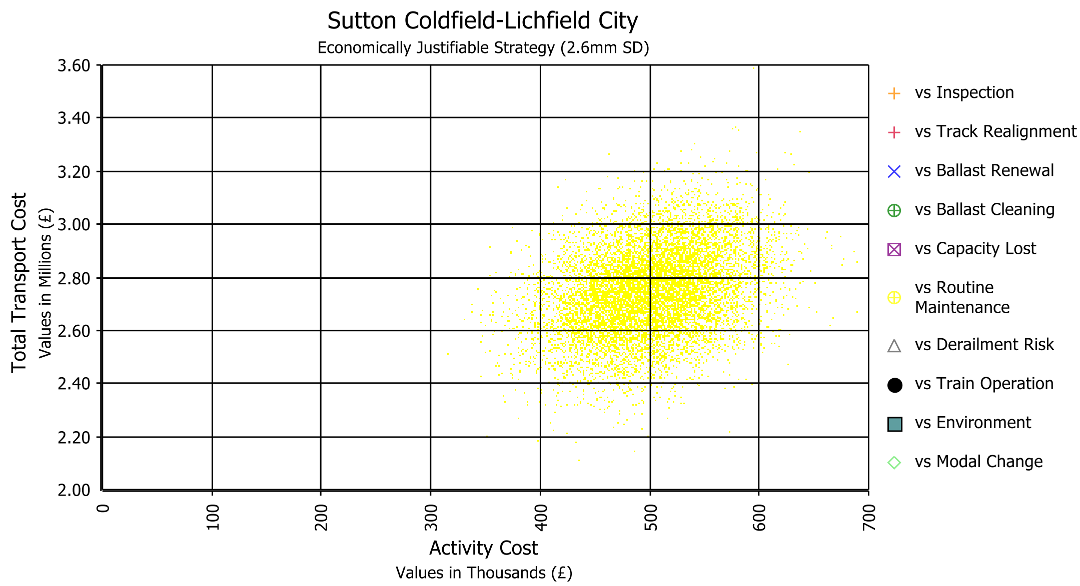


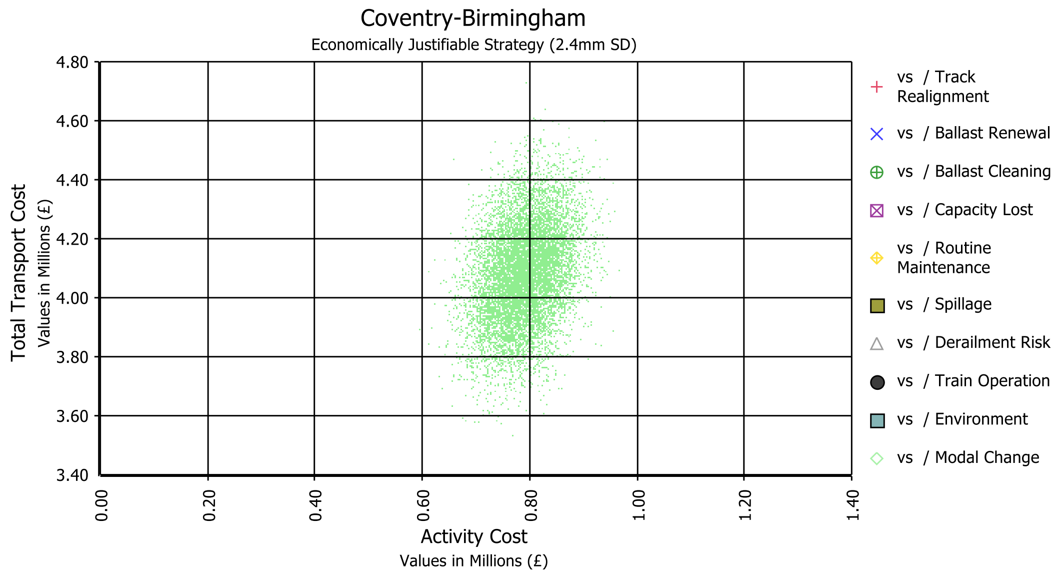
Figure 8 WLCCA results for Mixed-Freight Passenger Route with (a) NPV (b) Total Transport Cost (c) Construction Costs (d) Maintenance Costs and (e) Track Use Costs as a function of average Track Quality

A sensitivity analysis was carried out to quantify the contribution of different costs to maintenance and track use costs for the most economic strategies for the three routes (see Figures 9a-9c). The scatter plots were generated by running 10,000 Monte Carlo Simulations iterations for each WLCC component. By inspection of Figures 9a-9c, it may be seen that the track use costs were found to contribute the greatest to the total costs for the commuter route. The comparatively higher contribution of train operation costs for the commuter route is due to the more frequent train services on this route compared to the other two routes. This results in greater costs of delays for a given strategy. On the other hand, the environmental impacts and mode change costs are the highest contributors to total transport costs for the high-speed and mixed-traffic routes (see Figures 9b-9c). This highlights the potential benefits of reducing environmental emissions, road congestion and accidents through a shift from road to rail. Although the cost of at least one derailment is similar across all three routes, it is highest on the mixed freight route (Figure 9c). This is due to impact of a potential freight derailment on the passenger train operations on the route in the form of delays



(9a)

(9b)



(9c)

Figure 9 Contribution of cost elements of maintenance and track use to the Total Transport Cost for the economically justifiable strategy for (a) Commuter Route (b) High-Speed Passenger Route (c) Mixed-Freight Passenger Route

7. Concluding Discussion

Governments, on behalf of the taxpayer, seek to maximize the benefits derived from investment in railway infrastructure and train operation. To facilitate this process, the WLCCA approach proposed is an equitable and transparent means of evaluating the economics of maintenance strategies, which takes into account for the first time, the costs and benefits to all stakeholders. To this end, the WLCCA considers the costs associated with track construction, maintenance, track use and the end-of-life of the asset. To address the uncertainties associated within the data, a probabilistic approach using Monte Carlo Simulation was used to examine the unit costs and project the impacts and benefits of different strategies in terms of probability distributions.

The approach was demonstrated on three route types on the UK mainline railway network namely commuter, high-speed passenger and mixed passenger-freight routes. The results from the case studies showed that different maintenance strategies are required for each route to maximise economic benefits. Further, the track qualities associated with the economically beneficial strategies suggested by the approach differ from those used by Network Rail.

The case studies also illustrate the impact of maintenance effectiveness on the total maintenance cost. As it is expected, the worsening track quality increases the track use costs and decreases the maintenances costs. Such a trend is clearly visible in the projection of track maintenance and use costs associated with different maintenance strategies across all the three routes (see Figures 5b-c, 6b-c and 7b-c). The train operational cost per m is an important indicator of railway operational efficiency because it measures the level of financial inputs required per train (ITF, 2013). Although, the staff costs are a large component of these train operational costs, it was assumed for the study that they have remained constant throughout in line with the data presented in ORR (2015). However, greater benefits can be achieved if the staff costs and wages were modelled to increase over the period of time. The fuel consumption was modelled based on Zarembski et al. (2010) as data for the case study was not made available by the respective train operating companies. Using the actual train fuel costs may therefore give different results. Assuming that the number of train services remain the same throughout the analysis period, our study shows that, if the track condition was allowed to deteriorate from good to poor condition then train operating costs could rise by up to £500 per m annually through increases in fuel consumption and train maintenance across all three routes.

From Network Rail's perspective, it is financially preferable to carry out as little maintenance as possible e.g. the do-minimum strategy (see Figures 5b, 6b and 7b). However, the analysis suggests that if railway track use costs are considered then there are more economically and environmentally beneficial strategies. For example, for the high-speed passenger route, a maintenance standard of 2.4 mm SD instead of 2.6 mm SD would result in annual savings of approximately £3,000 per m. Considering the higher contribution of maintenance and train operation to the total transport costs for the commuter route (see Figure 8a), approximately £1,100 per m of annual savings could be achieved by maintaining the track at 2.4 mm SD instead of 2.6 mm SD. The above notwithstanding, it is interesting to note that for the mixed passenger-freight route a 10% reduction in total transport costs could be achieved by reducing the average track quality from the current SD of 1.2 mm to a SD of 2.4 mm. However, this section of the track serves Network Rail's headquarters and is therefore maintained in such a good condition for political reasons. Furthermore, it is noteworthy that the strategy chosen by Network Rail to maintain this section of track involves five ballast renewals and 15 track realignment operations over the track's lifecycle of 25 years (see Table 3). Maintaining the track condition to a slightly lower average track quality of 1.4 mm, a strategy that Network Rail uses on an adjacent section, could be achieved using three less ballast renewals and only five more track realignment operations. This would potentially save Network Rail approximately £16,000 annually.

The analysis also indicated that environmental impacts and mode change had the highest contribution to the total transport costs across all the route types (see Figures 8a-c). Reductions in environmental impacts can be achieved through eco-friendly construction and sustainable maintenance practices. For example, sourcing components such as sleepers, which contain recycled content, using where appropriate life-expired ballast within the sub-ballast ballast layer, reducing energy consumption on site and using renewable sources of power. Research is also on-going to develop plastic aggregates which can be used in the sub-ballast layer.

The proposed approach can thus be used to support strategic planning and programming levels of railway asset management (Robinson, 2008). For example, in the cases when there is a shortage in the annual track maintenance budget, the approach can be employed to inform plausible maintenance strategies that realise the maximum benefit for the available budget. Senior managers and decision makers can also use the approach advocated to improve long-term investment choices. For example, the approach allows the implications of reductions in maintenance budgets on total transport costs to be scrutinised and investment to be targeted to the areas of the railway network providing the greatest benefit.

For the analysis of large railway networks the approach would require a considerable amount of historical railway condition and maintenance and cost data. Much of this information is now routinely collected by railway infrastructure maintainers. However, the data requirements of the system, and therefore the computational time required to run the model and to analyse the results, can be reduced considerably by carefully selecting a sufficient number of representative track sections to portray adequately the characteristics of the entire network. A representative track section is considered to embody those sections of railway network which deteriorate at similar rates and have similar whole life cycle costs. An initial selection procedure could therefore utilize the construction standards and the speed and tonnage of the rolling stock utilizing track sections. Analyses such as those shown by Figure 9 could thereafter be used to refine the selected representative sections.

A number of countries have a vertically separated structure in which train operation and infrastructure provision are provided by different organisations. In such environments, infrastructure owners have little concern for the impact of track condition on train operating costs. Unless a suitable incentive scheme is provided by a regulator the infrastructure owner is likely to maintain the track at the lowest financial cost to meet track condition standards. These standards may not be the most economic nor may they be the most cost effective over the long term. Similarly, train operators also are unconcerned about the impact of poorly maintained vehicles on track damage. It is in the interests of all stakeholders and the environment, however, for the infrastructure and rolling stock to be maintained appropriately. The approach presented herein is a means by which the regulators of vertically separated railways can achieve this equitably and transparently.

Whether or not the operation of a railway is managed by a single entity or vertically separated, the use of the proposed approach is subject to the organization's culture and operational objectives. To overcome potential issues, stakeholders should be engaged to enable (i) improved appreciation of the WLCC approach and it's use in informing equitable decisions; (ii) access to accurate and reliable cost data, including track maintenance and train operation costs, and; (iii) more effective investment decision making which considers, on a WLCC basis, the costs and benefits to stakeholders and the environment.

Given that the life cycle of railway track can be 25 years or more, and maintenance interventions need to be planned several years in advance, future development of the proposed approach could consider a track possession planning model that takes into account the scheduling of track maintenance under operational constraints. The research carried out D'Ariano et al. (2019), Liden et al. (2017) and Luan et al. (2017), for example, would be useful in informing such further developments. For high speed rail in particular, the risks associated with track instability, ballast flight, vibrations and track constructed on soft soils could also be considered within the proposed approach.

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Notational List

$\widehat{B_n}$ are the benefits in the n^{th} year
$\widehat{C_n}$ are the costs accruing in the n^{th} year
$\hat{C}_{Bn}$ is the cost per metre of ballast material in year, *n*
$\hat{C}_{BCmn}$ is the cost of equipment, *m*, for ballast cleaning per metre in year, *n*
$\hat{C}_{BRmn}$ is the cost per metre of using equipment, *m*, for ballast renewal in year, *n*
$\hat{C}_{Cmn}$ is the cost per metre, of using a piece of equipment, m, for track construction in year, *n*
$\hat{C}_{CSmn}$ is the machinery cost per metre for cleaning up the spillage of materials using equipment, *m*
$\hat{C}_{DQn}$ is the average cost of a derailment on the track section during year, *n*
$\hat{C}_{Emn}$ is the average employee cost of operating a piece of equipment, *m*, in year, *n*.
$\hat{C}_{EnvImp}$ is the environmental impact cost due to a shift from other modes to railway transport
C_{EOImx} is the cost of using a piece of equipment, m, to dispose of, or recycle a track component, *x*, per metre
$\hat{C}_{FDn}$ is the average delay cost for a freight train in year, *n*
$\hat{C}_{FPnV}$ is the unit cost of fuel during year, *n*, for passenger train of type, *V*
$\hat{C}_{FFnV}$ is the unit cost of fuel during year, *n*, for freight train of type, *V*
$\hat{C}_{pIn}$ is the impact cost of pollutant type, *p*, on the environment during year, *n*
$\hat{C}_{PS}$ is the net benefit of a passenger vehicle journeys shifting to railways
$\hat{C}_{FS}$ is the net benefit of a freight vehicle journeys shifting to railways
$\hat{C}_{Prop}$ is the cost of land procured per metre
$\hat{C}_{PDn}$ is the average delay cost for a passenger train in year, *n*
$\hat{C}_{RMmn}$ is the cost per metre of equipment, *m*, used for routine maintenance in year, *n*
$\hat{C}_{RSLn}$ the cost of reduced service life of the track per year during year, *n*
$\hat{T}_{RSLn}$ is the mean reduced service life of the track in years, n
$\hat{C}_{TImn}$ is the cost of using a piece of equipment, *m*, per metre for a track inspection in year, *n*
$\hat{C}_{TRAmn}$ is the cost of using equipment, *m*, per metre for track realignment in year, *n*
$\hat{C}_{TSPnV(Q)}$ is the unit cost of spare parts during year, *n*, for the components of passenger train of type, *V*, for the average track quality, Q_A, achieved in year n.
$\hat{C}_{TSFnV(Q)}$ is the unit cost of spare parts during year, *n*, for the components of freight train of type, *V*, for the average track quality, Q_A, achieved in year n
$\hat{C}_{TMPnV(Q)}$ is the average train maintenance cost during year, *n*, for a passenger train of type, *V*, for an average track quality, Q_A, achieved in year n
$\hat{C}_{TMFnV(Q)}$ is the average train maintenance cost during year, *n*, for a freight train of type, *V*, for an average track quality, Q_A, achieved in year n
$\hat{E}_{pCn}$ is the environmental costs incurred during construction of railway track during year, *n*
$\hat{E}_{pMn}$ is the environmental costs incurred during maintenance of railway track during year, *n*
$\hat{E}_{pRn}$ is the environmental costs incurred during renewal of railway track during year, *n*
$\hat{E}_{pOn}$ is the environmental costs incurred during operation of railway track during year, *n*
$\hat{E}_{pDn}$ is the environmental costs incurred during disposal of railway track during year, *n*
$\hat{E}_{mn}$ is the average number of employees required to operate a piece of equipment, *m*, in year, *n*

$\hat{F}_{CPnV(Q)}$ is the total fuel consumed during year, *n*, by passenger train of type, *V*, for an average track quality, Q_A, achieved in year n
$\hat{F}_{CFnV(Q)}$ is the total fuel consumed during year, *n*, by freight train of type, *V*, for an average track quality, Q_A, achieved in year n
L is the length of the track section in metres
n is the specific year of the WLCCA period
$\hat{N}_{ARS}$ is the average reduction in the number of road accidents due to mode change
$\hat{T}_{APDMn}$ is average passenger train delay in minutes in year, *n*, due to track possession for maintenance
$\hat{T}_{AFDMn}$ is average freight train delay in minutes in year, *n*, due to track possession for maintenance
$\hat{N}_{FnV}$ is number of journeys on freight train type, *V*, through the track section during year,n
$\hat{N}_{FTDn}$ is average number of delayed freight trains in year, *n*, due to track possession for maintenance
$\hat{N}_{FTSRn}$ is average number of delayed passenger trains in year, *n*, due to speed restrictions
$\hat{N}_{FSQ}$ is the average number of freight vehicle journeys shifting to railways during time period, *n*, for the average track quality achieved during time period, *n*
$\hat{N}_{PTDn}$ *is* the number of delayed passenger trains in year, *n*, due to track possession for maintenance
$\hat{N}_{PSQ}$ is the average number of passenger vehicle journeys shifting to railways during time period, *n*, for the average track quality achieved during time period, *n*
$\hat{N}_{PTSRn}$ is average number of delayed passenger trains in year, *n*, due to speed restrictions
$\hat{N}_{TSPnV(Q)}$ is the average number of train components renewed during year, *n*, per passenger train type, *V,* for an average track quality, Q_A, achieved in year n
$\hat{N}_{TSFnV(Q)}$ is the average number of train components renewed during year, *n*, per freight train type, *V,* for an average track quality, Q_A, achieved in year n
$\hat{N}_{PnV}$ is the number of journeys on passenger train type, *V*, through the track section during year, *n*
P_{DQn} is the probability of at least one derailment occurring during year, *n*, on the track section of an average track quality, Q_A
$\hat{r}$ is the discount rate
R_{av} is the residual asset value
S_{RP} is average restricted speed for passenger trains along the track section
S_{RF} is average restricted speed for freight trains along the track section
S_L is the maximum permitted speed for trains along the track section
$\hat{T}_{APDMn}$ is average passenger train delay in minutes in year, *n*, due to track possession for maintenance
$\hat{T}_{AFDMn}$ is average freight train delay in minutes in year, *n*, due to track possession for maintenance
u is the number of times a piece of equipment, *m*, is used in year, *n*
$\widehat{VOL}$ is the average economic value of a person's life

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